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PROGRESS ON RESOLVING MAJOR SURETY ISSUES

by

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ABSTRACT

This paper presents a summary of the major surety issues that have been identified during Phase I of the SP-100 Program and the progress that has been made in analyzing the most important of these issues in the context of the conceptual design effort. These issues have been identified as inadvertent criticality, toxic material release and dispersion, radiation exposure following end-of-life reentry, potential diversion of special nuclear material, failure to achieve end-of-life neutronic shutdown, and structural predictability for end-of-life reentry or boost. Because of the complexity of these issues, a simplified conservative approach was taken during Phase I. Progress on these issues has been mainly in the areas of increased understanding of the issues, identification of design features to resolve the issues, and quantitative evaluations of the surety characteristics of the various design concepts.

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I. INTRODUCTION

During the initial part of the SP-100 program, the surety effort* was focused on the delineation, prioritization, and characterization of the surety issues. The objectives of the work done in the past year (FY 1985) have been to analyze the most important issues in the context of the conceptual design activities, to define definitively the basis for the surety evaluations of the competing concepts, to perform the surety evaluations

*Surety is the integration of safety, environmental protection, safeguards, reliability and quality assurance.

of the concepts as part of the overall concept selection process, and to generate safety, environmental protection, and safeguards goals and guidelines for the ground engineering system (GES) phase of the SP-100 program. In this paper, we will concentrate on the progress that has been made in understanding and dealing with the important issues.

II. BACKGROUND

Many of the surety issues of major importance are extremely difficult to address with high precision because of the extremely destructive and ill-defined accident environments that are involved and because of the highly complex, nonlinear transient response of an SP-100 reactor to these environments. For example, in launch accidents the blast effects could cause a wide spectrum of damage to an SP-100, depending on the particular accident mode in the Space Transportation System (STS), the explosion initiation site, the extent of propellant mixing, the nature of the blast wave (air shock, tank and orbiter debris, explosion products, or combinations), the orientation of the blast wave relative to an SP-100, and the structural characteristics of an SP-100. This spectrum could range from relatively minor disassembly of somewhat fragile components external to the reactor core but with the core remaining essentially intact to complete destruction of the entire power system. A damaged but essentially intact reactor could be subjected to an intense fire environment for an extended period of time as the solid propellant burns, leading to a potential for changing the core geometry and material constituency and for forming and dispersing any toxic materials that are part of an SP-100 The temperature and duration of such a fire would be highly variable, depending on the propellant breakup and distribution on the ground around an SP-100. As another example, high-velocity ground impacts of the reactor could occur either as a result of high-altitude ascent accidents or as a result of intact reentry. The damage to the reactor during these impacts may be highly variable, depending on the characteristics of the impact surfaces, the orientation of the reactor at impact, and the extent of prior damage by STS explosion or reentry heating. If criticality occurred as a result of core geometry or constituency changes, the reactor neutronic response could be extremely nonlinear, highly transient, and tightly coupled to the structural and fluid dynamic responses. These are examples of the types of problems that are involved in addressing the surety issues.

Because a complete analysis of these types of problems requires sophisticated and expensive techniques, it was not attempted during the first phase of the SP-100 program. In some cases, the data base is insufficient to support precise models, and therefore analyses, even if the program desired them. Thus, the decision was made to evaluate the issues based on specific assumed reactor states or specific assumed transients. This approach permitted the surety characteristics of the design concepts to be determined in a consistent way for comparison and permitted the feasibility of resolving the issues to be ascertained.

III. MAJOR SURETY ISSUES

A large number of individual issues were delineated in FY 1984[1] as each phase of a typical mission was considered. As we began to address these issues, it became clear that many had common features and could be evaluated within the envelope of concerns of a few, more generic, issues. These generic issues are listed in Table I.

Inadvertent criticality encompasses all the criticality concerns related to dynamic core compaction by launch explosions and ground impacts. It includes the immersion concerns associated with a damaged reactor (partially disassembled and/or partially compacted) impacting in water or soil. Also included are the concerns of configuration and composition changes in severe STS launch accident fires. Finally, this issue encompasses the concerns related to the removal of neutron absorbers from the core through either explosion or reentry effects.

Toxic materials of various types, quantities, and configurations are being considered in the candidate SP-100 designs. The release and dispersal of these materials during launch accidents, during reentry heating, and during high-velocity ground impact are the primary concerns.

A primary end-of-life issue that has high importance (possibly from the standpoint of real health effects but certainly from the standpoint of perceived health effects) is the exposure of individuals or groups of people to the residual radioactivity in an SP-100 following a planned or unplanned reentry. The real threat depends on the composition of the fuel and structural materials, the power level, the operating time, the time interval between last operation and reentry, the thermal/structural/dispersal behavior during reentry, the particular portion of the Earth's

TABLE I

PRIMARY SURETY ISSUES

- Inadvertent criticality
- Toxic material releases and dispersal
- Radiation exposure following end-of-life reentry
- Potential diversion of special nuclear material
- Failure to achieve end-of-life neutronic shutdown
- Structural predictability for end-of-life reentry or boost

surface affected, and the interdictory response by local authorities after reentry. The exposure could be by direct radiation from radioactive material scattered on the ground or handled by people unaware of the danger, by inhalation of released radioactive gases and radioactive particulates, or by ingestion of contaminated water or foodstuffs.

The potential for diversion of the special nuclear material used for fuel in an SP-100 is an issue that is particularly important in the near term, while weapons proliferation is a major, world-wide concern. Thus, the issue is focused primarily on the early mission phases (ascent accidents and aborts) and short-lived operational orbits with unplanned reentry. This issue is complicated by many nontechnical aspects such as speculation on the responses of potential diverter governments if presented with the material, obtaining permission to enter a country to retrieve the material, and the application of international political leverage to force an accounting, and possibly a relinquishing, of the material.

Failure to accomplish permanent neutronic shutdown at the end of the operational phase of a mission using an SP-100 is an important issue because of its potentially strong influence on the issue of radiation exposure following end-of-life reentry. If the reactor is not actively brought to a cold subcritical state, it could continue to operate at low power levels for many tens or even hundreds of years. Thus, the radiological source term in the reactor would not decay with time as desired, could make reactor disposal much more difficult and unpredictable, and could result in much greater radiation exposure risks if reentry occurred even if delayed by many tens or even hundreds of years. Failure to maintain the shutdown state once accomplished could have similar negative effects.

The issue of structural predictability at the time of reentry or reactor disposal by boosting (to a long-lived orbit) or deboosting (controlled reentry to a deep ocean) is extremely important if safe disposal is to be achieved. The aspects of this issue that must be considered are the effects of molten fuel on the reactor structural elements (reactor vessel and pin support plates), the potentially corrosive effects of fission products or fuel compounds on structural elements, long-term material compatibility, and space environment effects on the structural materials. This last issue and the preceeding one encompass the concerns of reactor operational reliability and control/protection system performance.

IV. PROGRESS ON MAJOR SURETY ISSUES

The first four of the major surety issues in Table I received the greatest emphasis during FY 1985. The remaining two were addressed briefly by the design contractors but were left to the next phase of the program to be considered in depth as the design and requirements become more definitive. The discussion of progress on the major surety issues will be focused only on the first four.

A. Inadvertent Criticality

1. Compaction. Several structural end states of each candidate design were defined and analyzed neutronically for criticality. This was done

for two reasons: (1) Any attempts to analyze the transient structural responses of the candidate designs were beyond the scope of effort for FY 1985 and (2) one-dimensional scoping assessments of the reactor material responses showed the potential for crushing the reactor core. It was found that full axial and radial compaction with the normal reflector material surrounding the core can be accommodated without undue negative influence on the design. The fuel pin arrays typically are packed very closely, thereby limiting the extent of possible compaction. The problem can be solved by designing removable neutron absorbers into the core. These absorbers must be capable of offsetting the effects of compaction and must remain in the core during all compaction events. Safety rods that penetrate the core appear to be a solution for this problem and also can be used as a means of gaining increased reliability in the reactor protection function and the end-of-life shutdown function.

2. Water Immersion and Flooding. As with compaction, the prediction of reactor structural responses for the full spectrum of potential accident loads was not possible. Further, it was not possible to assure complete destruction of the core before or as it entered a body of water either around the launch area or at reentry. The SNAP-10A safety test program[2] supported this conclusion. Therefore, we again looked at the potential for criticality through a spectrum of damaged reactor end states.

Apparently, the removal of external radial reflectors could be a common occurrence during launch explosions (even mild ones) or high-velocity impacts in water.[a] Thus, it was appropriate to consider a bare reactor in evaluating the problem. The crucial factor is the amount of water that can enter the core to facilitate neutron moderation. If the "as designed" cores were filled completely with water, the tendency toward criticality would be increased but not maximized because of under-moderation. The primary difficulty occurs if the reactor is damaged in a way that permits the fuel pins to spread, thereby letting more water into the core. The effect of fuel pin spreading was found to be very pronounced for small-diameter pins (~1 cm) of the type typically used in fast reactors and in the thermoelectric and stirling engine SP-100 designs. The effect was small for the large thermionic pins (~3 cm in diameter) that embody a relatively larger mass of nonfuel materials (the power conversion elements are in the core). The nonfuel materials become stronger neutron absorbers as the neutron spectrum is moderated by the water, which partially offsets the water's undesirable effect. The fuel is a strong absorber of highly moderated neutrons. Thus, as these neutrons enter the fuel from the water around each fuel pin, they are absorbed mainly in the surface layer of fuel, leaving the fuel in the center of a large pin underused and less effective. Again, the effect of the water is counteracted.

These studies showed that there are solutions to the water flooding problem. The removable neutron absorbers used to solve the compaction problem are effective here also, but many more would be needed for the small pin designs if they were the only approach used. A design could be complicated substantially if a large number of such rods were used. Built-in thermal neutron absorbers in the form of thick cladding, interstitial splines, vessel liners, and/or core dividers are also possibilities. The operational penalty for these approaches is additional fissile fuel. For larger power ratings (>100 kWe), there may be excess fuel available because of constraints on burnup and the desire to avoid partial enrichments. Thus, the penalty may not be significant.

3. Soil Immersion. Soil immersion could occur whenever an essentially intact reactor impacts soil at substantial velocity as in reentry impact or in an early ascent accident that releases the reactor and lets it fall back to the ground. Again, external reflectors are likely to be torn away from the core. Because the soil would act as a more restraining "fluid" than water, some core compaction appears possible. Thus, the end states chosen for neutronic analysis were partial core compaction (pin to pin contact but no fuel crushing) with typical soil surrounding the reactor vessel.

The compaction of the core and the loss of the neutron absorbers associated with the control drums was offset only partially by the reduced performance of the soil as the neutron reflector. The problem could be solved with the same internal absorber rods required for the compaction and water immersion problems.

4. Launch Fires. The melting points of the core materials for the SP-100 are generally above 2600 K for the refractory metal concepts. The thermal environment that the reactor could see is probably not sufficient to melt the structural and neutron absorber materials and clearly is not sufficient to melt the ceramic fuel. Because of the uncertainty in the effective fire temperature, we chose conservative end states in which all materials except the fuel or those with higher melting points than the thermodynamic flame temperature were assumed to be removed from the core. The remaining solid materials then were assumed to form a conical pile of rubble on the ground. Even though most of the structural and all of the control material was removed, the neutronic analysis showed substantial margins against criticality. Furthermore, thermal analyses performed by the design contractors showed incomplete melting of the core even in the most extreme fire environment. Thus, this concern appears to be eliminated, at least for the 100-kWe systems.

5. Inadvertent Neutron Absorber Removal. Clearly, the inadvertent removal of the in-core neutron absorbers, the rotation of all the control drums, or the closing of reflector segments could compromise the solutions discussed above. Further, the reactor must be capable of criticality by absorber removal or reflection changes if it is to operate. Thus, if inadvertent criticality is to be avoided, inadvertent absorber removal or reflector displacement must be avoided. The design contractors looked at possible concepts for pinning, latching, and restraining these elements. Solutions appear to be available.

B. Toxic Material Releases and Dispersal

The design concepts considered during FY 1985 all used hundreds of kilograms of beryllium as neutron reflector and/or radiator materials. Screening analysis of all materials used in the SP-100 designs led to the conclusion that beryllium is the primary hazardous material of concern because of the large quantity involved and its high toxicity. It can be released in severe launch explosions and severe impacts through a mechanical aerosolization process called spalling (particularly if it is in the brittle oxide or carbide forms). It also can be released in a launch fire or during reentry heating through burning, vaporization, and fluid dynamic aerosolization. The hazard is associated primarily with inhalation. Therefore, the beryllium or its compounds must be released as a fine aerosol (<10 μm in diameter) to constitute a threat.

The appropriate standard or limit to be used for accidental, one-time, short-duration exposure situations is unclear. A study was made at Los Alamos during FY 1985 of the existing regulations for beryllium to determine their basis and to attempt to construct a technically defendable and appropriate goal for concept evaluation and design guidance. The resulting recommendation for a short-term exposure goal was that no individual should be exposed to an air- borne concentration of more than 25 $\mu g/m^3$ of beryllium (as a metal or any of its compounds) for more than 30 min.

The potential releases of beryllium during launch accidents were evaluated based on the amounts and their characteristics (form and thickness) in the competing designs. These were coupled with the different accident characteristics to evaluate beryllium dispersal and resulting doses. The accidents must be defined in a consistent way; for example, an assumed severe explosion that could aerosolize the ceramic beryllium mechanically also may severely shatter the solid rocket propellant, leading to a high fuel burn rate and a very high plume rise. This would lead to greater dispersion of the aerosolized beryllium and reduced doses (more people may receive lower doses). The aerosolization rate also was found to be important. Beryllium that initially existed as thin layers (such as in the radiator) would be vaporized rapidly compared with beryllium in the 10-cm-thick neutron reflectors. The consistent but somewhat simplified evaluation indicated that the beryllium issue appears resolvable.

C. Radiation Exposure Following End-of-Life Reentry

A substantial effort was used to evaluate the radiation exposure characteristics (doses vs area affected) resulting from SP-100 reentries having various assumed reentry breakup behaviors. We determined that complete aerosolization of all radioactive materials at high altitude was not possible for the SP-100 designs being considered (refractory metals and ceramic fuels). Therefore, it was important to determine which reentry configurations (in terms of the extent of breakup and footprint sizes) tended to minimize the overall radiation threat. It was recognized that accidental reentry during a disposal boost or planned disposal reentry from a nuclear-safe orbit both lead to random impacts on the Earth's surface. Thus, any type of population zone (sparse, dense, developed, or undeveloped) may be affected, and all types must be considered.

It was found that an essentially intact reentry and subsequent impact of the reactor would minimize the radiation threat. One large source cannot seriously affect nearly as many people because it is impossible for as many people to be in the proximity of one radiation source as can be in the proximity of hundreds of sources. Also, the exposure time can be controlled and limited more easily if one source (as opposed to hundreds of widely scattered sources) is involved. Furthermore, the intact reactor impact has a strong potential for embedding the radioactive materials in the ground, providing shielding, whereas small pieces would impact the ground at lower terminal velocities and would be less likely to embed.

The essentially intact reentry also solves the problem of inadvertent possession and contact for long periods of time with small pieces of radioactive material that may have relatively large contact dose rates. This is a concern for niobium-based designs in which ^{94}Nb is generated as an activation product during reactor operation but decays with a half-life of 20 300 yr. Even with a long-lived orbit typical of those required for nearly complete fission product decay (300--500 yr), the ^{94}Nb will produce significant gamma radiation, with pieces of fuel clad or structural elements having contact doses on the order of 100 rem/h. The dose rate for a niobium-based SP-100 reactor as a function of decay time and distance from the intact core is shown in Fig. 1. The areas in which significant dose rates would exist are limited even for short decay times and no terrain shielding. Thus, large evacuation zones would not be required to control the situation. For 300 yr of decay, the dose at 1 m would be about 2.6 rem/h. Although avoidance of the end-of-life radiation issue is preferred, it appears that limited exposures to a small number of individuals reasonably could be assured if intact reentry can be achieved. Reentry analyses performed during FY 1985 give strong indications that intact reentry is not only likely but probably can be assured with confidence. The ability of the reactor to remain intact during impact to the point of limiting radioactive surface debris requires more investigation.

D. Potential Diversion of Special Nuclear Material

The control of the special nuclear material to be used in the SP-100 can be achieved with normally accepted practices while it is manufactured, shipped, tested, handled at the launch pad, and retained in the orbitor during normal flight or controlled aborts. However, uncontrolled events such as deployment or orbit transfer accidents or orbital decay reentries would produce safeguards challenges for which precedents, policies, and guidelines do not exist. To address this problem, we performed an analysis to quantify the likelihood of a significant quantity (25 kg) of highly enriched uranium being deposited in a potential diverter country. We assumed that the reentries were random and that the debris within the footprint was distributed uniformly. The length of the footprint was a variable. The results showed that the likelihood of such an occurrence, based on the present assessment of potential diverter countries, would be diminishingly small only for a footprint of global scale or for very small particles (<1 g). At the other end of the spectrum, for footprint lengths in the range of 0 to 200 km, the likelihood of the event would be equal to the fraction of the Earth's surface area represented by the aggregate areas of all potential diverter countries or about 0.06. For the intermediate range, starting with footprints larger than about 200 km, the likelihood increases substantially and becomes dependent on the total quantity

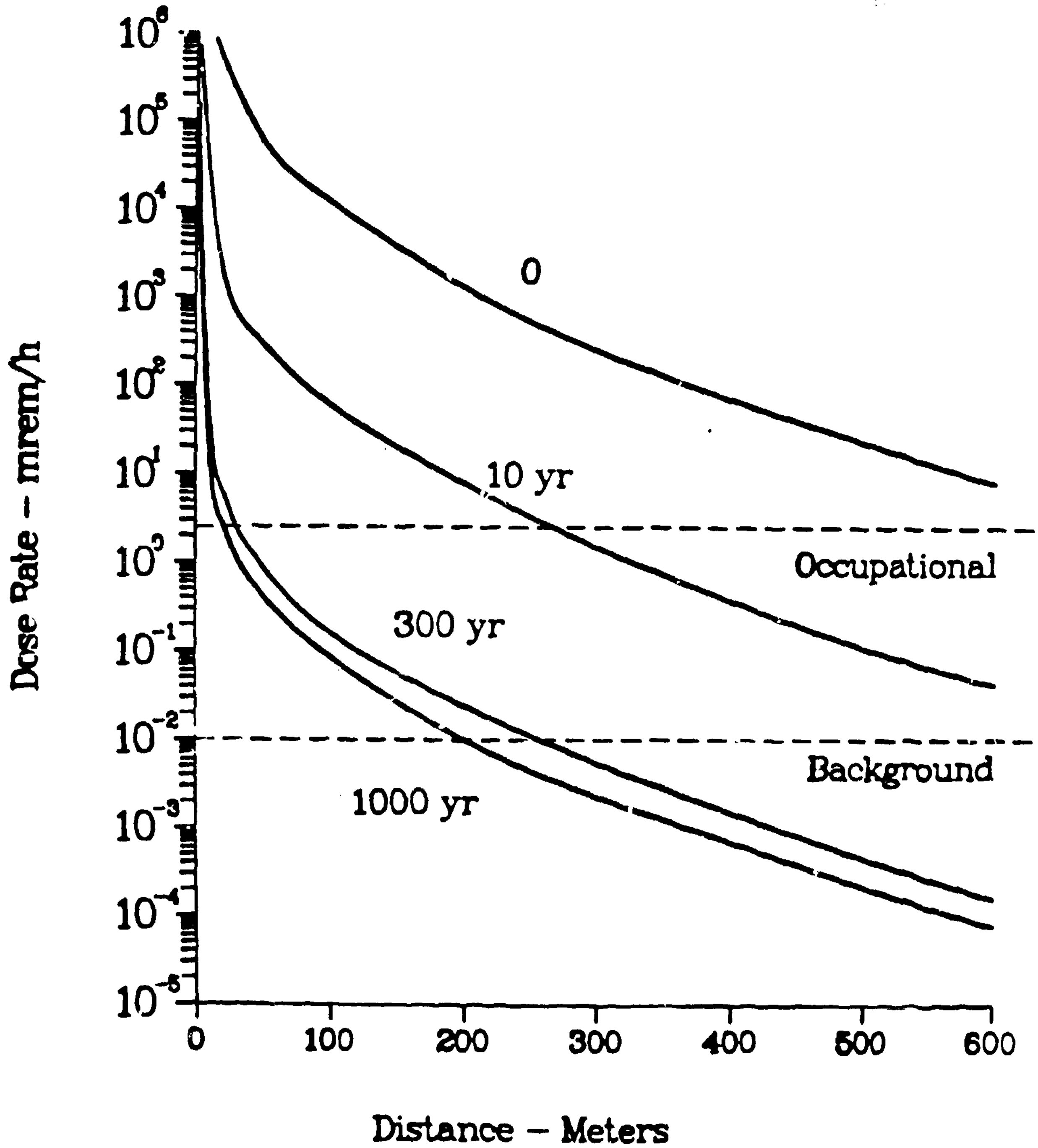

Fig. 1
Dose rate as a function of distance and decay time for an intact core.

of enriched uranium as well as the details of the modeling assumptions. Because global scattering of the reactor fuel appears impossible for current designs and widely scattered discrete pieces are undesirable from the safeguards standpoint, limiting the degree of reentry breakup appears desirable. Additional work is required on this issue to gain assurance of the acceptability of near intact reentry and therefore assurance of resolution of the safeguards issue.

V. SUMMARY

Substantial progress has been made in FY 1985 in the SP-100 surety area. This progress has been in the increased understanding of the important issues, in the quantification of technical aspects and trends, in the identification of design features to resolve issues, and in the quantitative evaluation of the surety characteristics of the various design concepts. Most of the important issues appear to be resolvable even with conservative, high-confidence approaches at the 100-kWe size. For larger reactors, less conservative approaches may be required and uncertainties may need substantial reduction. This will require the application of more sophisticated analysis approaches and the development of some additional data. A foundation has been laid for understanding the important issues. We can proceed with confidence into Phase II of the program knowing how to approach some of these difficult issues.

REFERENCES

1. H. Sullivan, "SP-100 Surety Program," in <u>SP-100 Program Proceedings of the First Program Integration Meeting</u>, Danvers, Massachusetts, June 13--15, 1984 (Jet Propulsion Laboratory report JPL D-1708 July 31, 1984), pp. 4-1 through 4-12.

2. J. M. Otter, K. E. Buttrey, and R. P. Johnson, "Aerospace Safety Program Summary Report," Rockwell International, Atomics International Division, report AI-AEC-13100 (July 30, 1973).